REMARKS

Claims 1-63 are in the application. Claims 1, 4-6, 23, 24, 26, 35, and 39-41 are amended in this Response. Claims 42-63 are new.

The amendments clarify that the claimed system and method are applicable to measuring properties of one or more films. These amendments are amply supported in the specification at, e.g., page 2, lines 29-31, page 5, page 8, lines 26-27, page 11, lines 6-7, Figure 5B and related discussion beginning at page 11, line 28.

New claims 42 and 44 specify that the one or more films may comprise a film stack, and new claims 43 and 44 specify that the film stack may comprise a vertical film stack. These claims are amply supported in the specification at, e.g., page 5, lines 8-9, Figure 5B and related discussion beginning at page 11, line 28.

New claims 46 and 47 specify that measurements may occur at one or more desired measurement locations and are similar to pending claims 6 and 26. These claims are amply supported in the specification at, e.g., page 11, lines 24-25, page 21, lines 25-29, and Figure 5A and related discussion beginning at page 11, line 23.

New claims 48 and 49 specify that the one or more measurement locations may be directed to different features of a patterned film. These claims are amply supported in the specification at. e.g., page 2, line 31, page 8, line 27, page 11, line 7, Figure 5B and related discussion beginning at page 11, line 29, page 18, line 2-3.

New claims 50 and 51 specify that the one or more desired measurement locations are located on a surface, and the reflected or transmitted light is nominally perpendicular to the surface. These claims are amply supported in page 16 of "Spectroscopic Ellipsometry and Reflectometry: A User's Guide," by Harland G. Tompkins and William A. McGahan, which is incorporated by reference into the specification at page 18, lines 16-18. Page 16 of the Tompkins reference includes Figure 2.6, showing that the angle of incidence of the incident light can be 90°. See attached excerpt from Tompkins reference, pages 11-21.

New claims 52 and 53 specify that the one or more desired measurement locations are located on a surface, and the reflected or transmitted light is at an angle to the surface. These

claims are amply supported by Figures 1, 3, 6A, and 6B, which illustrate incident light at an angle relative to the surface containing the desired measurement locations.

New claims 54 and 55 specify that the reflected or transmitted light is unpolarized. These claims are supported by page 14, Section 2.3.4, first sentence, in the Tompkins reference, which states that the light typically used in reflectometry is not intentionally polarized. See excerpt of Tompkins reference, pages 11-21, copy attached.

New claims 56 and 57 specify that the reflected or transmitted light is polarized. These claims are supported by page 14 of the Tompkins reference, in particular, Section 2.3.4, second sentence, Section 2.4.1, first sentence, and Section 2.4.2, which together state that ellipsometry is related to reflectometry insofar as both involve measuring reflected light from a surface of interest, and that ellipsometry involves the use of elliptically polarized light. See excerpt of Tompkins reference, pages 11-21, copy attached.

New claims 58 and 59 specify that the one or more properties relate to metal leads. These claims are amply supported in the specification at Figure 5B, which shows a semiconductor die area with possible measurement locations located at metal leads 512a, 512b, 512c or 510a, 510b, 510c; at page 18, line 3, which refers to features such as metal leads; and to page 19, lines 14-17, which states that the measurement process can be applied to other properties besides film thickness.

New claims 60 and 61 specify that the one or more properties relate to the spacing between metal leads. These claims are amply supported in the specification at Figure 5B, which shows a semiconductor die with possible measurement locations in the spacings between metal leads 512a, 512b, 512c or 510a, 510b, 510c; and to page 19, lines 14-17, which states that the measurement process can be applied to other properties besides film thickness.

New claims 62 and 63 specify that the system can be a reflectometry or ellipsometry system. These claims are amply supported by the Tompkins reference, incorporated by reference into the specification.

The Commissioner is authorized to charge the claims fee that is due in connection with this Preliminary Amendment, as well as any other fees that are due, to our Deposit Account **08-3038**, referencing Docket No. 02578.0006.CPUS01. Applicant is entitled to small entity status, so please reflect this status in any such charge.

Respectfully submitted,

HOWREY SIMON ARNOLD & WHITE LLP

Date: March 19, 2002

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Howrey Docket No. 02578.0006.CPUS01

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the application of:

Scott A. Chalmers, et al.

Appl. Serial No.: 09/899,383

Filed: July 3, 2001

For: METHOD AND APPARATUS FOR HIGH-SPEED THICKNESS MAPPING OF PATTERNED THIN FILMS

Art Unit:

Examiner:

OIPE JC26 MAR 27 2002 PATENT & TRADEMARK OFFICE

MARKED UP VERSION OF CLAIMS

Commissioner for Patents
Washington, D.C. 20231

Sir:

In accordance with 37 C.F.R. 1.121(c)(ii), a marked up version of prior pending claims, with all changes shown by the previously used convention comparison system (deletions in brackets, insertions underlined) follows:

1. (Once Amended) A system for measuring one or more properties of [a film]<u>one or more films</u> comprising:

a light source for directing light to the <u>one or more</u> film<u>s</u>;

a one-dimensional imaging spectrometer for receiving light reflected from or transmitted through a one dimensional pattern of spatial locations on the <u>one or more</u> film<u>s</u>, and determining therefrom a reflectance or transmission spectrum for one or more of the spatial locations in the pattern;

CERTIFICATE OF MAILING
(37 C.F.R. §1.8a)

I hereby certify that this paper (along with any referred to as being attached or enclosed) is being deposited with the United States Postal Service on the date shown below in an envelope addressed to Commissioner for Patents, Washington, D.C. 20231 with sufficient postage as First Class Mail.

March, 19 2002
Date of Deposit

Diana Vilkaitis
Name of Person Mailing Paper

Signature of Person Mailing Paper

a translation mechanism for relatively translating the one or more films with respect to the spectrometer; and

a processor for (a) obtaining from the spectrometer reflectance or transmission spectra for a plurality of one dimensional patterns of spatial locations along the one or more films; (b) aggregating these reflectance or transmission spectra to obtain reflectance or transmission spectra for a two dimensional area on the one or more films; and (c) determining therefrom one or more properties of the one or more films.

4. (Once Amended) The system of claim 1 in which the translation mechanism is configured to move a platform supporting the one or more films relative to the spectrometer or the spectrometer and light source.

5. (Once Amended) The system of claim 1 in which the translation mechanism is configured to move the spectrometer or spectrometer and light source relative to a platform supporting the one or more films.

6. (Once Amended) The system of claim 1 where the processor is configured to determine the one or more properties of the [layer]one or more films at one or more desired measurement locations.

23. (Once Amended) The system of claim 1 wherein the one-dimensional imaging spectrometer is configured to receive light reflected from or transmitted through a plurality of one dimensional patterns of spatial locations on the one or more films, and determining for each such pattern a reflectance or transmission spectrum for one or more of the spatial locations in the pattern, the spectrometer configured to provide resolution of 1 mm or better along both first and second spatial dimensions.

24. (Once Amended) A method for measuring one or more properties of [a]one or more films comprising:

directing light to the one or more films;

receiving light reflected from or transmitted through a one dimensional pattern of spatial locations on the one or more films, and determining therefrom a reflectance or transmission spectrum for one or more of the one dimensional spatial locations in the pattern;

obtaining reflectance or transmission spectra for additional one dimensional patterns of spatial locations on the one or more films;

aggregating these reflectance or transmission spectra to obtain reflectance or transmission spectra for a two dimensional area on the one or more films, and

determining therefrom one or more properties of the one or more films.

26. (Once Amended) The method of claim 24 further comprising determining the one or more properties of the one or more films at one or more desired measurement locations.

35. (Once Amended) The method of claim 24 further comprising obtaining reflectance or transmission spectra for successive one dimensional patterns of contiguous spatial locations along the one or more films in the shape of a line.

39. (Once Amended) The method of claim 38 further comprising receiving light reflected from or transmitted through a plurality of one dimensional patterns of spatial locations on the one or more films, and determining for each such pattern a reflectance or transmission spectrum for one or more of the one dimensional spatial locations in the pattern.

40. (Once Amended) A system for measuring one or more properties of [a]one or more films comprising:

means for directing light to the one or more films;

means for receiving light reflected from or transmitted through a one dimensional pattern of spatial locations on the one or more films, and determining therefrom a reflectance or transmission spectrum for one or more of the spatial locations in the pattern;

means for relatively translating the one or more films with respect to the spectrometer; and

means for (a) obtaining from the spectrometer reflectance or transmission spectra for a plurality of one dimensional patterns of spatial locations along the one or more films; (b) aggregating these reflectance or transmission spectra to obtain reflectance or transmission spectra for a two dimensional area on the one or more films; and (c) determining therefrom one or more properties of the one or more films.

41. (Once Amended) A method for measuring one or more properties of [a] one or more films comprising:

a step for directing light to the one or more films;

a step for receiving light reflected from or transmitted through a one dimensional pattern of spatial locations on the one or more films, and determining therefrom a reflectance or transmission spectrum for one or more of the one dimensional spatial locations in the pattern;

a step for obtaining reflectance or transmission spectra for additional one dimensional patterns of spatial locations on the one or more films;

a step for aggregating these reflectance or transmission spectra to obtain reflectance or transmission spectra for a two dimensional area on the one or more films, and

a step for determining therefrom one or more properties of the one or more films.

SPECTROSCOPIC ELLIPSOMETRY AND REFLECTOMETRY

A USER'S GUIDE

Harland G. Tompkins
Motorola, Inc.

William A. McGahan
Nanometrics, Inc.

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TABLE 2.1 Penetration Depths (Defined in Text) for Several Materials

Material	Wavelength (λ)	Extinction Coefficient (k)	Penetration Depth (D_p)
Single crystal Si[9]	6328 Å	0.016	~3.1 μm
Single crystal Si[10]	3009 Å	4.09	58 Å
Tungsten[11]	6328 Å	2.63	191 Å
Aluminum[11]	6328 Å	6.92	73 Å

We characterize the curve defined by Eq. 2.7 with a quantity which we will call the *penetration depth*. When the quantity αz is equal to 1.0, from Eq. 2.7, the intensity will have decreased by a factor of e^{-1} (about 37%) of its original value. We define[8] the penetration depth as the depth where this occurs, and denote it as D_p. From Eq. 2.8, this is given by

$$D_p = \frac{\lambda}{4\pi k} \tag{2.9}$$

(Note that in Eqs. 2.8 and 2.9, λ is the wavelength of light in free space rather than in the medium itself.)

We shall find that both the index of refraction and the extinction coefficient are functions of wavelength. The term *optical constants* is somewhat inappropriate. In addition, these quantities are also functions of temperature. The term *optical functions* is sometimes used. In keeping with common usage, however, we shall use the older term and, when appropriate, use the term *optical constant spectra* to denote the index of refraction and the extinction coefficient plotted as a function of either wavelength or photon energy.

Some examples of penetration depths are given in Table 2.1. In the case of single-crystal silicon, we show the value of k at two different wavelengths. Note that at a thickness of D_p, the intensity has dropped to 37% of its initial value, at $2 \times D_p$, it has dropped to 15%, at $3 \times D_p$, to 5%, and at $4 \times D_p$, to 2%. Hence, optical measurements only *see* about four penetration depths of a given material.

2.2.2. Laws of Reflection and Refraction

As suggested by Figure 2.2, some of the light is reflected at the interface and some is transmitted into the material. It was known by the ancients (Euclid, 300 BC) that the angle of reflection is equal to the angle of incidence, that is,

$$\phi_i = \phi_r \tag{2.10}$$

In Figure 2.2, both angles are listed as ϕ_1. The law of refraction is somewhat more involved and is called *Snell's law* after Willebrord Snell, who discovered the principal in 1621. Snell's law, in its most general form, is

$$\tilde{N}_1 \sin \phi_1 = \tilde{N}_2 \sin \phi_2 \tag{2.11}$$

This is derived in Appendix C.

When dealing with a dielectric material, that is, $k = 0$, the law simplifies to the more familiar

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \tag{2.12}$$

All of the terms in Eq. 2.12 are real numbers. For Eq. 2.11, generally $k = 0$ for the ambient, hence $\tilde{N}_1$ is real, and the sine function for medium 1 is a real number (as we would expect). If $\tilde{N}_2$ is a complex number (k_2 is nonzero) then the sine function in medium 2 is a complex function rather than the familiar function (opposite side over the hypotenuse).[12] There is a corresponding complex cosine function such that

$$\sin^2 \phi_2 + \cos^2 \phi_2 = 1 \tag{2.13}$$

We shall find that we use the complex cosine function in Fresnel's equations and we use Eq. 2.13 along with Snell's law to determine its value.

2.3 POLARIZED LIGHT

2.3.1 Sources

When a given photon is emitted from an incandescent source, its electric field is oriented in a given direction. The electric field of the next photon will be oriented in a different direction, and in general photons are emitted with electric fields oriented in all different directions. This is called *unpolarized* light. If we arrange for all the photons in our light beam to be oriented in a given direction, the light is referred to as *polarized* light. One familiar way to do this is to pass the light through an optical element which only allows light having one particular orientation to pass through. Another method is to have a light source which emits polarized light. Whereas incandescent light sources are unpolarized, most lasers emit light which is more or less polarized.

2.3.2 Linearly Polarized Light

In Figure 2.3, we depict the electric field strength for two light beams with the same frequency and the same amplitude traveling along the same path. We

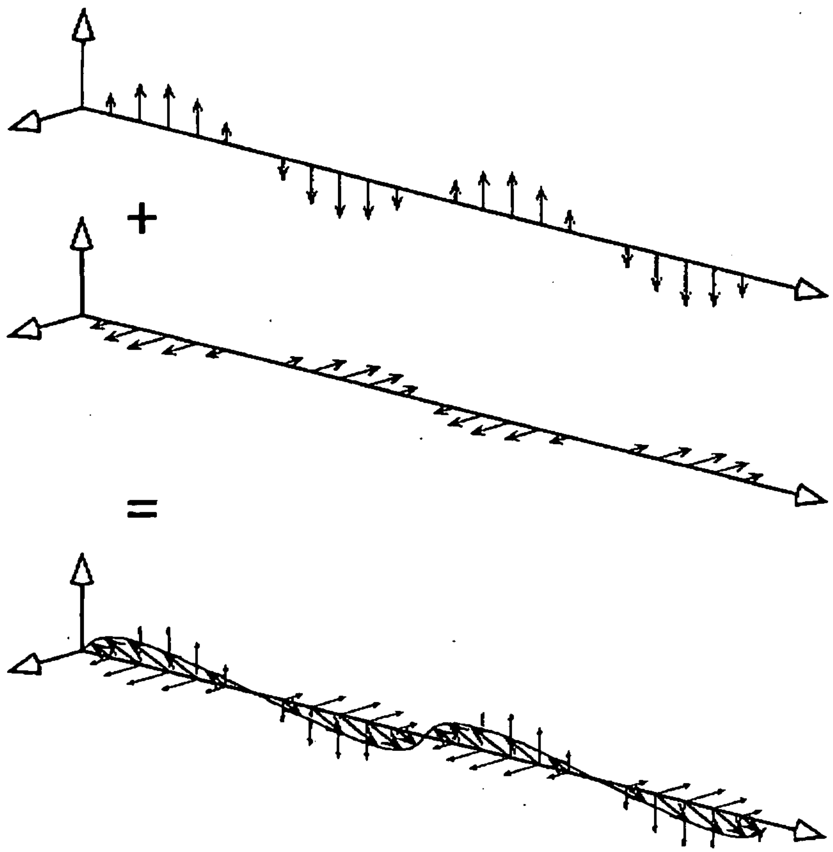

Figure 2.3 Combining two linearly polarized light beams which are in phase and have the same frequency produces linearly polarized light.

direction and one is polarized in the horizontal direction. In this case, note specifically that the maximum, minimum, and zero points of the vertical wave coincide with those of the horizontal wave, that is, the waves are *in phase*. When the vector sums of the components of the two waves are added at each point in space, the resultant wave is a linear wave which is polarized at 45° to the vertical. If all other conditions were the same, but the amplitudes were not equal, the result would have been a linear polarized wave at an angle different from 45°. Specifically, *when two linearly polarized waves with the same frequency are combined in phase, the resultant wave is linearly polarized.*

2.3.3 Elliptically Polarized Light

In Figure 2.4, we again depict two light beams with the same frequency and amplitude traveling along the same path. Again, one is polarized vertically and

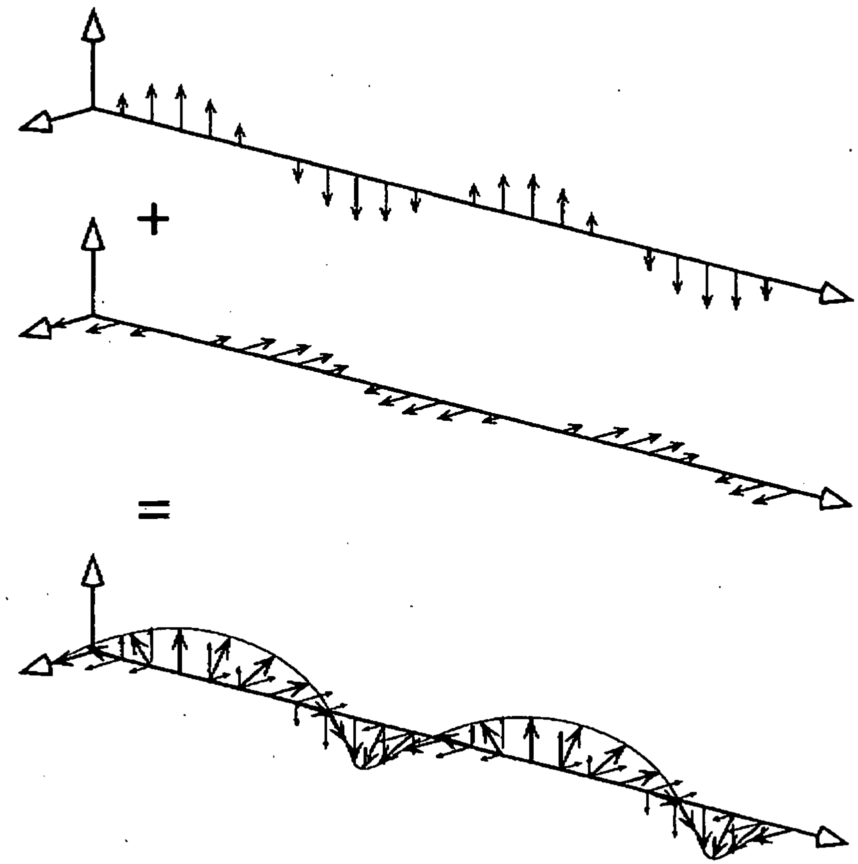

Figure 2.4 Combining two linearly polarized light beams which are a quarter wave out of phase and which have the same frequency and amplitude will produce circularly polarized light.

the other is polarized horizontally. In this case, however, the maximum, zero, and minimum of the electric field strength of the horizontal wave have been displaced from those of the vertical wave (in this particular example, the two waves are *out of phase* by 90°.) When the two waves are combined, the tips of the arrows of the resultant wave do not move back and forth in a plane, as was the case in the previous illustration. Instead, they move in a manner which, if viewed end-on, would describe a circle. This is called circularly polarized light. Had the phase shift been anything other than 90°, or had the amplitudes not been equal, the tips of the arrows would have appeared to be moving on an ellipse, if viewed end-on, and this is referred to as elliptically polarized light. Specifically, *when two linearly polarized waves with the same frequency are combined out of phase, the resultant wave is elliptically polarized.* Linearly polarized light and circularly polarized light are specific cases of the more general elliptically polarized light

2.3.4 Application of Elliptically Polarized Light

The light used in most reflectometry instruments is not intentionally polarized. Elliptically polarized light is used in ellipsometry, and in fact is the reason for the name ellipsometry. Elliptically polarized light is generated when linearly polarized light reflects from a surface under certain conditions. The amount of ellipticity which is induced depends on the surface (optical constants, presence of films, etc.). A second method for changing the ellipticity of polarized light is to pass the light beam through certain specific optical elements. By directing our light beam at materials of interest, we use it as a probe. We use our optical elements to determine how much ellipticity was induced from the reflection and then calculate from this the properties (optical constants, thicknesses of films, etc.) of our material of interest.

2.4 THE REFLECTION OF LIGHT

2.4.1 Orientation

Both reflectometry and ellipsometry involve the light making a reflection from the surface of interest. In order to write the equations which describe the effect of the reflection on the incident light, it is necessary to define a reference plane. Figure 2.5 shows schematically a light beam reflecting from the surface. The incident beam and the direction normal to the surface define a plane which is perpendicular to the surface and this is called the *plane of incidence*. Note that the outgoing beam is also in the plane of incidence. As indicated in Figure 2.2, the angle of incidence is the angle between the light beam and the normal to the surface. The effect of the reflection depends on the polarization state of the incoming light and the angle of incidence. In Figure 2.5 we show the amplitude of the electric wave which is waving in the plane of incidence as E_p and the amplitude of the electric wave which is waving perpendicular to the plane of

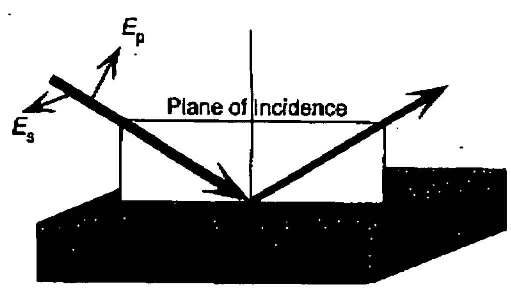

Figure 2.5 The plane of incidence is defined as the plane which contains both the incoming beam and the normal to the surface. The amplitude of the electric field wave in the plane of incidence and perpendicular to the plane of incidence are called E_p and E_s, respectively.

incidence as E_s. These waves are referred to as p-waves and s-waves, respectively. The subscripts "s" and "p" stand for the German words "senkrecht" and "parallel."

2.4.2 The Reflection Equations of Fresnel

The reflectance, denoted herein as "$\Re$", is the ratio of the *intensity* of the outgoing light compared to that of the incoming light. This is the quantity which is measured in all reflectance instruments. Recall that the intensity is proportional to the square of the amplitude of the wave.

In addition to the reflectance, we are also interested in the ratio of the *amplitude* of the outgoing wave compared to that of the incoming wave. We first focus on a single interface and will develop the more general case later. When only one interface is considered, this ratio is called the *Fresnel reflection coefficient*, and it will be different for s-waves and p-waves. As suggested by Figure 2.2, let us suppose that the interface separates medium 1 and medium 2, with respective indices of refraction $\tilde{N}_1$ and $\tilde{N}_2$ and angles of incidence and refraction ϕ_1 and ϕ_2 (related by Snell's law). When the beam is incident from medium 1 onto medium 2, the Fresnel reflection coefficients are given by

$$r_{12}^p = \frac{\tilde{N}_2 \cos\phi_1 - \tilde{N}_1 \cos\phi_2}{\tilde{N}_2 \cos\phi_1 + \tilde{N}_1 \cos\phi_2} \qquad r_{12}^s = \frac{\tilde{N}_1 \cos\phi_1 - \tilde{N}_2 \cos\phi_2}{\tilde{N}_1 \cos\phi_1 + \tilde{N}_2 \cos\phi_2} \tag{2.14}$$

where the superscripts refer to either p-waves or s-waves and the subscripts refer to the media which the interface separates. Corresponding equations exist for transmission. The reflection and transmission coefficient equations are derived in Appendix C.

2.4.3 The Brewster Angle

For light incident from air onto dielectrics, that is, when $k = 0$, all of the terms in the Fresnel equations above are real numbers. Figure 2.6A shows a plot of both of the Fresnel coefficients as a function of angle of incidence for a material such as TiO_2 which has an index of refraction $n = 2.2$ at a wavelength of 6328 Å. At normal incidence, r^p and r^s have equal magnitudes but opposite signs. For a single interface, the reflectance is simply the square of the Fresnel reflection coefficient. Figure 2.6B shows the reflectance, $\Re$, also plotted versus angle of incidence. At normal incidence, all of the cosine terms are equal to +1 and we have

$$r_{12}^p = \frac{n_2 - 1}{n_2 + 1} \qquad r_{12}^s = \frac{1 - n_2}{1 + n_2} \qquad \Re^p = \Re^s = \left(\frac{n_2 - 1}{n_2 + 1}\right)^2 \tag{2.15}$$

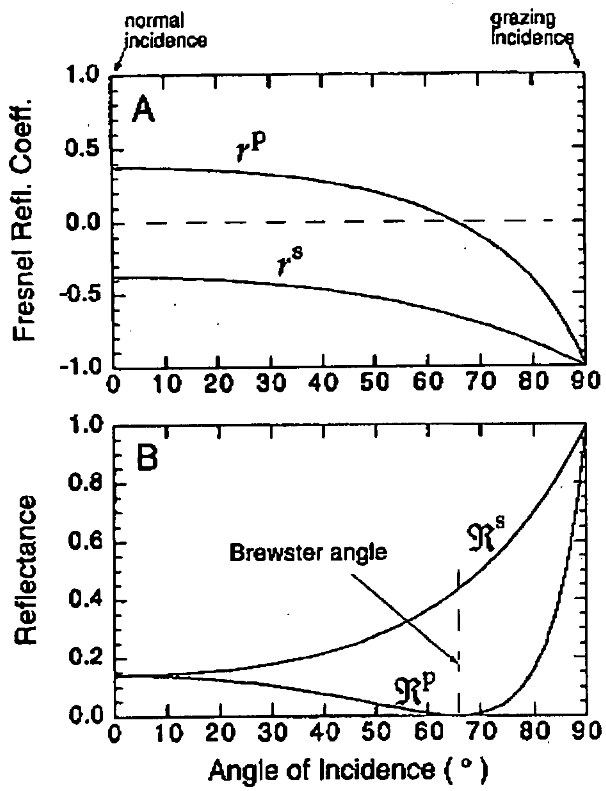

Figure 2.6 (A) The Fresnel reflection coefficients, and (B) the reflectance, plotted versus the angle of incidence for light incident from air onto a dielectric such as TiO_2 with $n = 2.2$ and $k = 0$, at a wavelength of 6328 Å. At the Brewster angle, all of the reflected light is polarized with the electric vector perpendicular to the plane of incidence.

The reflectance of the two waves must be equal at normal incidence since the plane of incidence is no longer uniquely defined.

For other than normal incidence, we see that r^s is always negative and nonzero, whereas r^p is positive for angles near-normal, passes through zero, and is negative for near-grazing angles of incidence. This can be rationalized algebraically[13] from the relationship $n_2 > n_1$ and $\cos \phi_1 > 0$.

At the angle of incidence where r^p is zero, the reflectance $\Re^p$ is also zero; hence all of the reflected light is polarized perpendicular to the plane of incidence. This is shown in Figure 2.6 as the *Brewster angle*. This phenomena was discovered by David Brewster[14] in the early 1800s. This angle is also known as the *polarizing angle* and sometimes the *principal angle*.

Two significant ramifications of the Brewster angle are that at that angle, designated as ϕ_B,

$$\tan \phi_B = \frac{n_2}{n_1} \tag{2.16}$$

and

$$\cos \phi_2 = \sin \phi_B \tag{2.17}$$

which is to say that the angle between the reflected beam and the transmitted beam is a right angle. One additional feature of the Brewster angle for dielectrics is that this is the incidence angle where the phase shift of the p-wave on reflection shifts abruptly from zero to 180°. No such shift occurs for the s-wave.

The Brewster angle is a function of the index of refraction and, as indicated earlier, the index of refraction is a function of wavelength; hence the Brewster angle is a function of wavelength. The term *Brewster wavelength* is sometimes used with a single angle of incidence. This is simply the wavelength where the value of the index of refraction matches the Brewster condition for that angle of incidence.

The concept of the Brewster angle or polarizing angle is used routinely by photographers in photographing objects which are under water. The light coming from the underwater object (fish or alligators) is often significantly less that the light reflected from the top surface of the water, and the reflected light will obscure the underwater object. If the angle of incidence of the reflected light is roughly equal to the Brewster angle, a polarizer adjusted to the correct azimuth will remove the reflected light, allowing the camera to capture the light from the underwater object.

At the Brewster angle, although the reflected light is polarized in one direction only, the transmitted light still has components of both polarizations. Multiple interfaces can be used to remove successively more and more of the perpendicular polarized light until the transmitted light is virtually pure polarized light in the plane of incidence. Historically,[15] this is one method of obtaining polarized light.

When the reflecting surface is not a dielectric, that is, k is nonzero, the situation becomes more complicated. The Fresnel reflection coefficients and r^s are now complex numbers and the concepts of greater than zero and less than zero have no meaning. Normally, there is no situation where both the real and imaginary parts of the complex number are zero; hence there is no analogous version for Figure 2.6A for metals or semiconductors. The reflectance values, $\Re^p$, and $\Re^s$, are real numbers, however, defined as the square of the magnitudes of r^p and r^s, and can be plotted, as shown in Figure 2.7, for tantalum. Although $\Re^p$ does not go to zero, it does go through a minimum at an angle which is called the principal angle.

As the angle of incidence increases, the phase difference between the p-wave and the s-wave shifts gradually, rather than abruptly as for a dielectric (at the Brewster angle). For metals, as for all other materials, the phase difference passes through 90° at the principal angle. This will be discussed in detail in Chapter 6 (see Figure 6.3).

It should be noted that high reflectance is obtained when the index of the substrate is significantly different from that of the ambient. This can occur

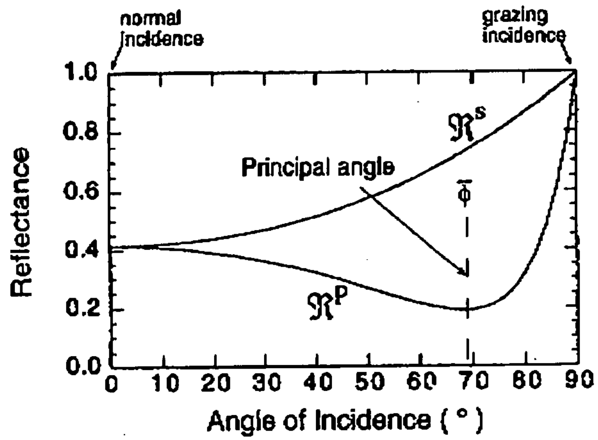

Figure 2.7 The reflectance, plotted versus the angle of incidence for a metal such as Ta with $n = 1.72$ and $k = 2.09$ at a wavelength of 6328 Å.

when n_2 is significantly different from 1.0 or when k_2 is large (significantly different from zero).

2.4.4 Reflections with Films

When more than one interface is present, that is, with a film, the light which is transmitted across the first interface cannot be ignored, as was the case in the previous section. As suggested by Figure 2.8, the resultant reflected wave returning to medium 1 will consist of light which is initially reflected from the first interface as well as light which is transmitted by the first interface, reflected from the second interface, and then transmitted by the first interface going in the reverse direction, and so on. Each successive transmission back

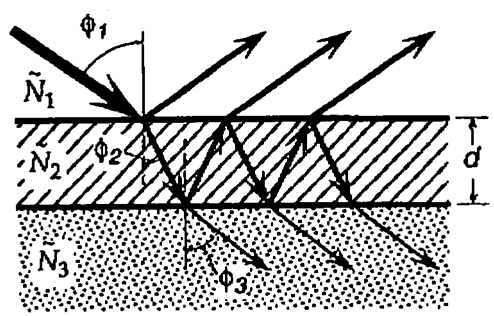

Figure 2.8 Reflections and transmissions for two interfaces. The resultant reflected beam is made up of the initially reflected beam and the infinite series of beams which are transmitted from medium 2 back into medium 1.

into medium 1 is smaller than the last, and the infinite series of partial waves makes up the resultant reflected wave.

From a macroscopic point of view, the quantities of interest are the amplitude of the incoming wave and the amplitude of the resultant outgoing wave. For the reflectometry technique, we are interested in the intensity, or the square of the amplitude. For the ellipsometry technique, we are interested in the phase and amplitude relationships between the p-wave and the s-wave.

The ratio of the amplitude of the outgoing resultant wave to the amplitude of the incoming wave is defined as the *total reflection coefficient*, and is analogous to the Fresnel reflection coefficients for a single interface. For a single film (two interfaces) this is

$$R^p = \frac{r_{12}^p + r_{23}^p \exp(-j2\beta)}{1 + r_{12}^p r_{23}^p \exp(-j2\beta)} \qquad R^s = \frac{r_{12}^s + r_{23}^s \exp(-j2\beta)}{1 + r_{12}^s r_{23}^s \exp(-j2\beta)} \tag{2.18}$$

where

$$\beta = 2\pi\left(\frac{d}{\lambda}\right)\tilde{N}_2 \cos\phi_2 \tag{2.19}$$

These equations are derived in Appendix C.

When $k \neq 0$ the Fresnel coefficients, $\tilde{N}_2$, and $\cos\phi_2$ (and hence β) are complex numbers. When $k = 0$, these numbers are real. In general, except for very special circumstances, R^p and R^s are complex numbers. β is the phase change in the wave, as it moves from the top of the film to the bottom of the film. Hence, 2β is the phase difference between the part of the wave reflecting from the top surface and the part of the wave which has traversed the film twice (in and out).

For multiple films, the expressions on the right-hand side of Eq. 2.18 can be used in an iterative way[16,17] to determine the total reflection coefficient for the entire stack. For the rapid calculation needed in regression analysis,[18] some form of a matrix method is often used.

2.5 ELLIPSOMETRY AND REFLECTOMETRY DEFINITIONS

2.5.1 Reflectance

The reflectance is defined as the ratio of the intensity of the outgoing wave to the intensity of the incoming wave. The total reflection coefficients R^p and R^s are defined above as the ratio of the amplitude of the outgoing wave to the amplitude of the incoming wave. Hence, the reflectance is the square of the magnitude of the total reflection coefficient, that is,

$$\mathfrak{R}^p = |R^p|^2 \quad \text{and} \quad \mathfrak{R}^s = |R^s|^2 \tag{2.20}$$

For a single interface (no film), the total reflection coefficients reduce to the Fresnel reflection coefficients.

Most reflectance measurements are made at normal or near-normal incidence. Under these conditions, all of the cosine terms are equal to unity, and as suggested in Eq. 2.15, there is no distinction between the p-waves and the s-waves.

2.5.2 Delta and Psi

Figure 2.5 shows the p-waves and s-waves and, in general, they are not necessarily in phase. When each makes a reflection, there is the possibility of a phase shift and the shift is not necessarily the same for the different waves. Let us denote the phase difference between the p-wave and the s-wave before the reflection as δ_1 and the phase difference after the reflection as δ_2. We define the parameter Δ, called *delta* (and often abbreviated as *Del*), as

$$\Delta = \delta_1 - \delta_2 \tag{2.21}$$

Delta, then, is the phase shift which is induced by the reflection, and its value can be from $-180°$ to $+180°$ (or alternatively, from zero to 360°).

In addition to a phase shift, the reflection will also induce an amplitude reduction for both the p-wave and the s-wave, and again, it will not necessarily be the same for the two types of wave. The total reflection coefficient for the p-wave and for the s-wave is defined as the ratio of the outgoing wave amplitude to the incoming amplitude and, in general, this is a complex number. $|R^p|$ and $|R^s|$ are the magnitudes of these amplitude diminutions. We define the quantity Ψ in such a manner that

$$\tan \Psi = \frac{|R^p|}{|R^s|} \tag{2.22}$$

Ψ is the angle whose tangent is the ratio of the magnitudes of the total reflection coefficients, and its value can range from zero to 90°.

2.5.3 The Fundamental Equation of Ellipsometry

Whereas $\tan \Psi$ is defined as the ratio of the magnitudes of the total reflection coefficients, and is hence a real number, we define a complex number ρ (rho) to be the complex ratio of the total reflection coefficients, that is,

$$\rho = \frac{R^p}{R^s} \tag{2.23}$$

The fundamental equation of ellipsometry[19] then is

$$\rho = \tan \Psi e^{i\Delta} \quad \text{or} \quad \tan \Psi e^{i\Delta} = \frac{R^p}{R^s} \tag{2.24}$$

The magnitude of ρ is contained in the $\tan \Psi$ part and the phase of ρ is contained in the exponential function. The quantities Ψ and Δ (sometimes only $\cos \Delta$) are measured by ellipsometers. These are properties of our probing light beam. The information about our sample is contained in the total reflection coefficients, and hence in ρ. It should be noted that assuming that our instrument is operating correctly, the quantities Δ and Ψ which are measured are always correct. Whether the quantities such as thickness and the optical constants which we deduce are correct or not depends on whether or not we have assumed the correct model. As an example of this, incorrect values of n and k can be deduced if we assume that our material is a substrate when in fact we have a thin layer of one material on top of a substrate of another material.

This simply makes the point that the quantities which ellipsometers measure are Δ and Ψ. Quantities such as thickness are calculated quantities based on an assumed model.

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